Postprint of the White Dwarf–Neutron Star Binary Model for Repeating Fast Radio Bursts

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Abstract

Fast Radio Bursts (FRBs) are brief, bright radio pulses of extragalactic origin, classified into repeating and non-repeating categories. The recurrent bursting behavior of repeating FRBs may originate from a compact binary system comprising a neutron star with a strong dipole magnetic field and a magnetized white dwarf. When the white dwarf fills its Roche lobe, material is transferred onto the neutron star surface through the inner Lagrangian point. Following a burst event, the white dwarf may be kicked away and subsequently re-accreted during its evolutionary process, thereby producing the repeating burst phenomenon. Based on observational data from the repeating fast radio bursts FRB 121102 and FRB 180916, we investigate the relationship between the time interval of two successive bursts and the fluence of the preceding burst within the white dwarf-neutron star binary model. Through comparison of theoretical predictions with observational values, we confirm that such an intermittent Roche-lobe overflow mechanism may explain the recurrent bursting behavior of repeating FRBs.

Full Text

The White Dwarf-Neutron Star Binary Model of Repeating Fast Radio Bursts

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Abstract

Fast Radio Bursts (FRBs) are brief, luminous radio pulses of extragalactic origin that exhibit two distinct populations: repeating and non-repeating FRBs. The recurrent bursting behavior of repeating FRBs may originate from a compact binary system comprising a neutron star with a strong dipole magnetic field and a magnetized white dwarf. When the white dwarf fills its Roche lobe, mass transfer occurs through the inner Lagrange point onto the neutron star surface. Following each burst event, the white dwarf may be dynamically ejected, only to resume accretion later in its evolutionary trajectory, thereby realizing repeated burst phenomena. Based on observational data from the repeating FRBs 121102 and 180916, we investigate the relationship between the time interval separating two consecutive bursts and the fluence of the preceding burst within the white dwarf-neutron star binary framework. Through comparison of theoretical predictions with observational measurements, we confirm that such an intermittent Roche lobe overflow mechanism may successfully explain the repetitive behavior of repeating FRBs.

Keywords: Fast Radio Bursts, white dwarf, accretion, gravitational radiation, magnetic reconnection

1 Introduction

Fast Radio Bursts (FRBs) are transient radio pulses with durations ranging from microseconds to milliseconds and flux densities reaching Jansky levels. These phenomena are classified into two categories: repeating and non-repeating FRBs. The high dispersion measures observed for FRBs suggest an extragalactic, possibly cosmological, origin. The first identification of a host galaxy for FRB 121102 confirmed the cosmological nature of FRBs, while also establishing it as the first observed repeating burst source. To date, the physical origin of FRBs remains enigmatic, though the properties of their host galaxies and local environments may provide crucial clues.

FRB 121102, the first FRB successfully associated with a host galaxy, is localized to a low-metallicity dwarf galaxy at redshift $z = 0.19273 \pm 0.00008$ undergoing active star formation. Repeating FRB 180916, localized to a star-forming region in a nearby massive spiral galaxy at redshift $z = 0.0337 \pm 0.0002$, represents the closest known source with an identified host and redshift. Despite the substantial differences between their host galaxies, both sources are situated within or adjacent to star-forming regions.

Although extensive follow-up observations were conducted after the discovery of FRB 121102, no additional repeating FRBs were detected until the 2018 launch of CHIME (the Canadian Hydrogen Intensity Mapping Experiment). CHIME is a novel meridian-transit radio telescope operating in the 400–800 MHz band, whose large collecting area, broad bandwidth, high sensitivity, enormous field of view, and powerful correlator render it an exceptional FRB detector. This instrument has created significant opportunities for testing existing theories and guiding subsequent observations. Since its launch, CHIME/FRB has continuously observed 18 new repeating FRBs, including FRB 180916.J0158+65, which exhibit characteristics distinct from non-repeating bursts.

Numerous physical models have been proposed to explain the origin of repeating

FRBs, with neutron stars featuring prominently in most scenarios. These include soft gamma repeaters, pulsars traversing asteroid belts, giant pulses from young pulsars, curvature radiation from strongly magnetized neutron stars, and binary systems containing a magnetized white dwarf paired with a neutron star possessing a strong dipole field. Lin et al. previously employed an intermittent Roche lobe overflow mechanism to interpret the repeating behavior of FRB 121102 based on 41 burst events. In this work, we compile data from 82 repeating bursts of FRB 121102 and 28 bursts of FRB 180916, focusing on consecutive bursts during continuous observation periods. By comparing the theoretical and observational relationships between the time interval separating adjacent bursts and the fluence of the preceding burst, we assess the viability of the white dwarf-neutron star binary model for explaining repeating FRB behavior.

2 Theoretical Model Analysis

In a binary system where both components are smaller than their respective Roche lobes, the system remains detached, preventing gravitational accretion between the stars. However, in a binary comprising a magnetized white dwarf and a neutron star with a strong dipole magnetic field, orbital separation may decrease through mechanisms such as gravitational radiation, causing the white dwarf to fill its Roche lobe and transforming the system into a semi-detached configuration. This initiates mass transfer from the white dwarf to the neutron star through the inner Lagrange point. Upon reaching the neutron star surface, the accreted material triggers magnetic reconnection that can accelerate electrons to extreme relativistic velocities instantaneously. The accretion process involves inward mass flow accompanied by outward angular momentum transport. Angular momentum conservation dictates that mass transfer proceeds continuously when the mass ratio $q > 2/3$ (where q represents the white dwarf to neutron star mass ratio). Conversely, if $q < 2/3$, the white dwarf may be ejected after accreting a portion of its mass, causing the system to become detached once again. Subsequent orbital evolution through gravitational radiation can then restore the semi-detached configuration, initiating a second mass transfer episode and manifesting as repeating burst behavior. Therefore, for white dwarf-neutron star binaries with $q < 2/3$, intermittent Roche lobe overflow may represent a common phenomenon.

For a white dwarf-neutron star binary with $q < 2/3$, the relationship between the time interval Δt separating two adjacent mass transfer episodes and the mass transferred during the first episode ΔM_2 is given by reference [7]:

[Equation (1) is referenced but not explicitly shown in the original text.]

However, estimating the exact number of electrons accelerated to extreme relativistic velocities proves challenging in this model. We therefore estimate the released energy through the magnetic energy carried by the accreted material, yielding the relationship between the fluence F of the preceding burst and ΔM_2 [7]:

$$F\Delta\nu D_L^2\Delta\theta = -\eta_1\eta_2\Delta M_{2c}^2 \quad (2)$$

where Δ represents the radio frequency bandwidth, D_L the luminosity distance, Δ the solid angle of the FRB, $_1$ the ratio of curvature radiation energy to total magnetic energy of the accreted material (representing energy release efficiency), $_2$ the ratio of magnetic field energy density to material density (representing magnetic reconnection efficiency), and c the speed of light.

Combining equations (1) and (2), we obtain the relationship between F and Δt:

$$\Delta t = 2.68 \times 10^{10}\frac{F\Delta\nu D_L^2\Delta\theta}{\eta_1\eta_{2c}^2} \quad (3)$$

For our calculations, we adopt Δ = 1 GHz and Δ = 0.04π (equivalent to 1% of the full sky). To compute $_2 = 8\pi\bar{\rho}c^2$, we select a white dwarf magnetic field strength B_{WD} 10^8 G (consistent with observations of 10^3–10^9 G fields in over 100 white dwarfs) and a mean atmospheric density $\bar{\rho} = 10^{-3}$ g cm^{-3}. For D_L calculations, we adopt cosmological parameters Ω_M = 0.286, Ω_Λ = 0.714, and H_0 = 69.6 km s^{-1} Mpc^{-1}.

3 Observational Data and Conclusions

As an exceptional FRB detector, the CHIME satellite has dramatically increased the number of detected FRBs and repeating sources since its launch. We have compiled 19 repeating FRBs along with their burst counts, presented in Table 1 . To date, FRB 121102 remains the most frequently bursting repeater, with our dataset comprising 82 bursts from this source [8,10]. For the remaining 18 repeaters, our focus on the relationship between time intervals and fluences of consecutive bursts during continuous observation periods renders only FRB 121102 and FRB 180916 suitable for interpreting the intermittent Roche lobe behavior.

FRB 121102, at redshift z = 0.19273, yields a luminosity distance D_L = 947.7 Mpc using our adopted cosmological parameters. FRB 180916, at z = 0.0337, corresponds to D_L = 149 Mpc. From the 82 bursts of FRB 121102, we extract 58 time intervals, while the 28 bursts of FRB 180916 provide 7 intervals, as listed in Table 2 (the first 19 intervals for FRB 121102 appear in Table 1 of reference [8]).

Based on the observational data in Table 2 and Table 1 of reference [8], we derive the relationship between time intervals Δt and preceding burst fluence F for these two repeating FRBs, shown as star symbols in Figure 1 [Figure 1: see original paper] (left panel: FRB 121102; right panel: FRB 180916), where Δt represents the rest-frame time interval. The three solid curves illustrate theoretical predictions from equation (3) for energy release efficiencies $_1$ = 0.002, 0.02, and 0.2. The observational data for both FRB 121102 and FRB 180916 generally fall within the range bounded by these three theoretical curves, suggesting consistency between theory and observations. This result implies that the neutron star-white dwarf binary model may successfully explain the repeating behavior of both FRB 121102 and FRB 180916.

FRBs represent a mysterious radio trans phenomenon characterized by cosmological distances and enormous energy outputs. The intermittent bursting behavior of a white dwarf-neutron star binary system may account for the repetitive nature of repeating FRBs. In such a system containing a magnetized white dwarf and a neutron star with a strong dipole magnetic field, mass transfer from the white dwarf to the neutron star commences when the white dwarf fills its Roche lobe. Upon reaching the neutron star surface, the magnetized material can trigger magnetic reconnection and radiation emission. However, angular momentum conservation may dominate over inward motion due to gravitational radiation during the transfer process, potentially ejecting the white dwarf after each burst and returning the system to a detached state. The next burst occurs only when gravitational radiation restores the semi-detached configuration, allowing the accretion and magnetic reconnection processes to repeat. The burst timescale is thought to correspond to the magnetic reconnection timescale, while the interval between adjacent bursts derives from its relationship with the mass transferred during the first event. Our focus centers on investigating the correlation between the time interval Δt separating consecutive bursts and the fluence F of the preceding burst. According to this model, equation (1) indicates that greater mass transfer during a burst event ejects the white dwarf farther, resulting in longer waiting times. Meanwhile, for known redshifts, equation (2) predicts that such bursts should exhibit higher fluence (see theoretical curves in Figure 1). Observationally, we obtain 58 Δt-F pairs from 82 repeating bursts of FRB 121102 and 7 pairs from 28 bursts of FRB 180916 (star symbols in Figure 1). We find that most observational results fall between the three theoretical curves, indicating basic consistency between theory and data. This suggests that the intermittent Roche lobe overflow mechanism may explain the repeating behavior of FRBs. One data point from September 20, 2016, deviates significantly from theoretical predictions, though the accuracy of its fluence measurement requires careful verification [8].

Numerous theoretical models currently attempt to explain the physical origin of repeating FRBs, but limited observational data have prevented definitive confirmation of any particular model. We anticipate that observations from CHIME/FRB and the Square Kilometre Array (SKA) will usher in a promising era for radio astronomy. As more data become available, we can effectively constrain existing physical models. Our interpretation of these two repeaters requires specification of multiple parameters; with additional repeating FRBs and more extensive observations of individual sources, we will acquire the data needed to further test this theoretical framework.

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Note: Figure translations are in progress. See original paper for figures.